NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

Technical Report
TR-2085-ENV

TCNOISE: A COMPUTER PROGRAM TO CALCULATE NOISE LEVELS AND DIRECTIVITY FROM A JET ENGINE TEST CELL

by

T.W. Lancey, California State University, Fullerton
C.A. Kodres, NFESC

October 1997

Sponsored by
Chief of Naval Operations
Safety and Occupational Health Division
Washington, DC 22217

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-018

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1997	Not final; May 1997 to July 1997

4. TITLE AND SUBTITLE

TCNOISE: A COMPUTER PROGRAM TO CALCULATE NOISE LEVELS AND DIRECTIVITY FROM A JET ENGINE TEST CELL

5. FUNDING NUMBERS

6. AUTHOR(S)

C.A. Kodres, NFESC
T.W. Lancey, California State University, Fullerton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(S)

Naval Facilities Engineering Service Center
1100 23rd Ave.
Port Hueneme, CA 93043-4370

8. PERFORMING ORGANIZATION REPORT NUMBER

TR-2085-ENV

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESSES

Chief of Naval Operations
Safety and Occupational Health Division (N45)
Washington, DC 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report presents the Fortran program TCNOISE (Test Cell NOISE). The program predicts noise emitted by jet engine test cells. It is to be used in conjunction with the Naval Facilities Engineering Service Center's jet engine test cell aerothermal performance computer model, reading output files from this code to acquire the flow properties necessary for the calculation of jet noise and surface noise. The theoretical basis of TCNOISE, instructions for running the program, example runs, and comparisons of program predictions with measured noise emissions are included in the report.

14. SUBJECT TERMS

Jet engine test cell, hush house, model, noise emissions, jet noise

15. NUMBER OF PAGES

37

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	
Unclassified	Unclassified	Unclassified	UL

EXECUTIVE SUMMARY

Noise emissions from the Navy's standard T-10 jet engine test cells are exceeding their design limits. This is a problem, in particular, for test facilities that are near residential areas. Several Naval Air Stations have received official complaints from adjacent neighborhoods. As the expansion of other communities brings them closer to jet engine test facilities, this problem will continue to grow.

Noise is an aerothermal phenomenon, and there are several active programs that could result in changes to the aerothermal characteristics of the Navy's test cells. Solving one problem while unknowingly exacerbating another problem would be a mistake. To avoid this, the development of a test cell noise emissions model was made an early milestone in the Naval Facilities Engineering Service Center's (NFESC) jet engine test cell NOx reduction project. The model will be used to determine changes in noise emissions that would be induced by test cell modifications made to decrease chemical and particulate emissions. It can also be used to quantitatively evaluate cell modifications specifically for the purpose of decreasing noise.

This report is a user's manual for the computer program TCNOISE (Test Cell NOISE), a Fortran code that predicts noise emitted by jet engine test cells. It is to be used in conjunction with the NFESC's jet engine test cell aerothermal performance model, reading output files from this program to acquire the flow properties necessary for the calculation of jet noise and surface noise. The theoretical basis of TCNOISE, instructions for running the program, and example runs are included in the report.

The accuracy of TCNOISE is assessed by comparing predicted noise emissions with sound pressure levels measured when the J52 and the TF30 engines were tested in the T-10 test cell at NAS Cubi Point, Republic of the Philippines, and the F404 was tested in Test Cell No. 3 at NAS Lemoore, California. Differences between calculated sound pressure levels and measured values are typically near 1 dB, with the maximum difference less than 3 dB.

Most test cell modifications affect noise generation by changing gas velocities and turbulence. However, three test cell dimensions that influence noise emissions have relatively small or no effect on noise generation: the length of the tube, the height of the exhaust stack, and the augmenter shell diameter. The influence of these dimensions can be examined without first rerunning the aerothermal model. Of these parameters, the effect of increasing the height of the exhaust stack is the most pronounced. For example, if the height of the exhaust stack of Test Cell No. 3 at NAS Lemoore is increased to approximately the height of the intake stack, far field noise, during tests of an afterburning F414 engine, will be decreased by about 7 dB.

Another Navy program that could affect noise emissions from jet engine test cells is the switch from a round to a square augmenter tube. TCNOISE predicts the Navy's T-10 test cell with a 13.7-foot square augmenter tube to be about 0.5 dB noisier than the standard T-10. Although gas velocities and turbulence through the square tube are lower because of the larger cross-sectional area, the jet noise is approximately 13 percent greater. This is primarily attributable to the lack of a transition section at the beginning of the augmenter tube to smooth out the flow.

CONTENTS

BACKGROUND

Noise emissions from the Navy's standard T-10 jet engine test cells are exceeding their design limit. This is a problem, in particular, for test facilities that are near residential areas. Several Naval Air Stations have received official complaints from adjacent neighborhoods. As the expansion of other communities brings them closer to jet engine test facilities, this problem will continue to grow.

Noise is an aerothermal phenomenon, and there are several active programs that could results in changes to the aerothermal characteristics of the Navy's test cells. Solving one problem while unknowingly exacerbating another problem would be a mistake. To avoid this, the development of a model to predict test cell noise emissions was made an early milestone in the Naval Facilities Engineering Service Center's (NFESC) jet engine test cell NOx reduction project. The model will be used to determine changes in noise emissions that would be induced by test cell modifications made to decrease chemical and particulate emissions. It can also be used to quantitatively evaluate cell modifications specifically for the purpose of decreasing noise.

This report is a user's manual for the Fortran model TCNOISE (Test Cell NOISE). The program predicts noise emitted by jet engine test cells. The program is run in conjunction with NFESC's jet engine test cell aerothermal performance computer model (Kodres, 1996), reading output files from this code to acquire the flow properties necessary for the calculation of jet noise and surface noise. The theoretical basis of TCNOISE, instructions for running the program, example runs, and comparisons of program predictions with measured noise emissions are included in the report.

THEORETICAL/MATHEMATICAL BASIS OF PROGRAM

The acoustical calculations of this program are centered around the noise producing mechanisms of jet (and self) noise, surface noise, and the reverberant noise field in the augmenter section. Noise reduction techniques considered are absorption in the augmenter section, the reactive muffler effect of the augmenter section, the diffraction of the exit ramp as a barrier, the refraction of the noise emanating from the jet, the noise reduction across the augmenter shell, the directivity of the sound emanating from the end of the augmenter tube, and the spherical divergence of the noise as it travels through the air to the stations 250 feet (76.2 meters) from the jet nozzle.

Jet Noise

The jet noise is calculated using the results of several research programs and combining jet shear noise with self noise (Jones, 1965; Lush, 1971; MacGregor, 1973):

$$W = 0.00004\rho U^8 D^2/c^5 \quad \text{(Watts)} \tag{1}$$

where W is the acoustic power, ρ the gas density, U the jet velocity, D the jet diameter, and c the ambient velocity of sound; all are in consistent SI units.

Effects of refraction in the jet are considered at 180 degrees (on-axis) where the refraction reduces the transmitted sound by 15.8 dB, and at 150 degrees, where the sound is increased 5.3 dB (Morris, 1973). These effects decrease at lower angles. This has a direct bearing on sound incident on the augmenter wall, but which alone provides a 41 dB attenuation so that the sound transmitted through the wall is much less than that transmitted out the augmenter tube.

Surface Noise

Equations for the prediction of the surface noise are also provided in the literature (Ffowcs, 1972; Nelson, 1982). With the Strouhal Number (St) at a given frequency (f) defined as $St \equiv f\,D/U$ and setting $\sigma = 0.03$ (the open area ratio of the augmenter tube), $z = 12.56637$ St is used in the solution for a Struve function of the first kind,

$$ALST = 0.0063662((z^{0.67})-(z^{0.089})+(z^{0.0038})) \tag{2}$$

The surface noise per unit area (WA) is then calculated using:

$$WA = \rho\pi^3(TI)^2U^6St(ALST)/96\sigma c^3 \tag{3}$$

where TI is the turbulence intensity.

Noise Reverberation and Absorption

The steady state reverberant field is given by:

$$WR = (W+WA/AS)/a \tag{4}$$

where AS is the duct sound producing surface area and a is the absorptivity of the augmenter section,

$$a = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \text{- - -} + \alpha_n S_n \tag{5}$$

The α_i's are the absorption coefficients and the S_i's are the surface areas of the ith surfaces in the augmenter section.

Noise Reduction

Reactive Muffler. Noise reduction caused by the expansion and contraction of the augmenter section is given by Wilson (1989) as:

$$TL = 10Log[1+ 0.25(m-1/m)^2\sin^2(kC)] \tag{6}$$

where m = augmenter shell area/augmenter tube area, k is the wave number ($k = 2\pi f/c$), and C is the augmenter tube length.

Diffraction over Ramp Barrier. Noise reduction is accomplished by the diffraction of sound as it crosses the exit ramp (Wilson, 1989), here treated as a barrier. The noise reduction is calculated approximately by:

$$TL = 5 + 20\mathrm{Log}[(2\pi N)^{0.5}/\tanh((2\pi N)^{0.5})] \qquad (7)$$

where N = 2f(A+B-C)/c, and A is the distance from the top of the augmenter tube to the top of the ramp, B is the distance from the top of the ramp to the 250-foot station, and C is the straight line distance from the top of the augmenter tube to the 250-foot station.

Directivity of Sound Leaving Augmenter Tube. The directivity of the sound is similar to that of a round piston (Kinsler, 1962). The directivity relative to the on-axis maximum at 180 degrees is

$$I/I_0 = [2J_1(X)/X]^2 \qquad (8)$$

I is the intensity at angle 180-θ and X=ka sinθ, where 'a' is the radius of the augmenter tube. $J_1(X)$ is the Bessel function of the first kind and order one.

Attenuation by Spherical Divergence. The reduction in intensity level as the spherical wave grows from R to r is

$$\mathrm{DeltaIL} = 20\ \mathrm{Log}[R/r] \qquad (9)$$

USER'S MANUAL

TCNOISE is a Fortran 90 program, solving Equations 1 through 9 for test cell noise emissions and far field sound pressure levels. It was developed and compiled using the Lahey LF90 compiler (Lahey, 1995). The program is being distributed with both the Fortran listing of the code, TCNOISE.FOR, and the compiled version, TCNOISE.EXE. If a compiler is available, the code can be modified and run, for example, when the augmenter tube grid is changed. The compiled program can be run by simply typing its name. A listing of the code is included as an appendix to this report.

The program requires output files from NFESC's jet engine test cell aerothermal performance model as input. The aerothermal model uses the Phoenics CFD code (Spalding, 1996) to solve the governing equations. The main section of TCNOISE reads the Phoenics output file required for the jet noise calculation, NOISE.JET, and calls subroutines that calculate jet and surface noise and reverberation. The Phoenics file used for surface noise calculations, NOISE.WAL, is read from the surface noise subroutine. The format for the Phoenics files to be read into the NOISE.JET and NOISE.WAL files of TCNOISE is (2F10.1, F10.4, E13.3, 3I5). These files contain velocity, temperature, gas density, and turbulent kinetic energy of pertinent Phoenics nodes, as well as the "I,J,K" location of that node within the test cell.

In the jet noise subroutine, noise generated in the individual nodes is calculated using Equation 1 with node gas velocities acquired from the Phoenics input and the average cross-

section dimension of the node. The individual node noise is summed over all nodes, and the acoustic power is written to the output file SPLOUT to verify that the more distant nodes contribute little to the overall acoustic power. The noise from an afterburning TF30 is calculated using Equation 1 but with the nozzle velocity and diameter of the jet as input. This provides a reference for the acoustic power.

Noise through the augmenter tube wall is also calculated. This is accomplished in three steps. First, the transmission losses across the pillows (10 dB), wall liner (1.5 dB), and the steel tube (41 dB) are set. Second, the geometric expansion of the spherical wave from the engine to the wall, at angles of 30, 60, and 90 degrees off-axis are calculated. Third, the effects of the jet refraction at off-axis angles of 30 degrees (+5.3 dB), 60 degrees (+3.0 dB), 90 degrees (+1.0), and 120 degrees (-5.0 dB) are added.

In the surface noise subroutine, the surface noise is calculated using the Phoenics output to acquire gas velocities and turbulence intensity along the augmenter tube wall for approximately the final 60 percent of the tube. The acoustic power for each element is summed as the calculations proceed.

The reverberation calculation uses the acoustic power from the jet and surface noise subroutines. The sum of these sources is considered to be the total noise source within the augmenter tube. Absorbing objects are the pillows, wall liner, and the tube entrance and exit, where sound is 100 percent transmitted. The surface areas of the pillows and the wall liner are calculated and multiplied by their respective absorption coefficients to yield the individual component absorptive areas. These areas are then summed to yield the total effective absorptive areas of the wall liner, the pillows, and the entrance and exit. Reverberant acoustic intensity is found by dividing the source acoustic power (in watts) by the effective absorptive area (in square meters).

Noise reduction of the test cell varies with the frequency (engine size and exit velocity). Maximum noise from the test cell is on-axis, and the results indicate that the noise reduction from the source at the engine exit to the on-axis 250-foot station is approximately 37 dB, but is dependent on frequency. If there were no test cell present, refractive effects would cause the maximum noise to occur at approximately 30 degrees off-axis where the jet noise field would be amplified by 5.3 dB. The noise reduction would therefore be approximately 42 dB, comparing the noise at 30 degrees with no test cell to the on-axis noise with the test cell.

Instructions for Running TCNOISE

The compiled Fortran program is TCNOISE.EXE. Phoenics output files for jet noise and for surface (wall) noise are presumed to be in files named *filename*.jet and *filename*.wal, respectively. Examples of these files are included in subsequent sections. The following procedure is required to run TCNOISE:

1. Type -- COPY *FILENAME*.JET NOISE.JET
   COPY *FILENAME*.WAL NOISE.WAL
   (the program recognizes only these file names)

2. Type -- TCNOISE (running the compiled version of the program)

3. The user is then prompted to enter the:

(i) AUGMENTER TUBE DIAMETER (all dimensions are in meters, e.g., 3.505 meters for Test Cell No. 3 at NAS Lemoore and 4.175 meters for the T-10 at NAS Cubi Point)

(ii) AUGMENTER SHELL DIAMETER (e.g., 5.5 meters for the T-10 test cells)

(iii) AUGMENTER TUBE LENGTH (e.g., 18.3 meters for Test Cell No. 3 at NAS Lemoore; 24.63 meters for the T-10 test cells)

(iv) THE INTEGER, 10 OR 14, DEPENDING ON WHETHER THE AUGMENTER TUBE DIAMETER IS NEAR 10 FEET (3.048 METERS) OR 14 FEET (4.27 METERS)

(v) THE VERTICAL DISTANCE FROM THE AUGMENTER TUBE TO THE TOP OF THE RAMP (e.g., 2.18 meters for Test Cell No. 3 at NAS Lemoore and 1.52 meters for the T-10 at NAS Cubi Point)

(vi) NUMBER OF SURFACE NODES IN THE AXIAL DIRECTION, AN INTEGER DEPENDING ON THE AUGMENTER TUBE LENGTH (the number of cells the augmenter tube was divided into for the aerothermal calculations (Kodres, 1996), e.g., 25 for Test Cell No. 3 at NAS Lemoore and 30 for the T-10 test cell at NAS Cubi Point)

Output

The output is printed on the monitor screen and sent to the file SPLOUT. Examples of output files are included in subsequent sections:

- The top 16 lines of SPLOUT list the acoustic power at each of the first 16 axial stations (as defined in the aerothermal code) downstream of the engine; they show the relatively small contribution of the more distant stations to the total jet acoustic power.

- Line 17 shows the jet acoustic power of the afterburning TF30 engine as calculated using Lighthill's theory with an empirical constant applied.

- Line 18 shows the total jet acoustic power predicted by TCNOISE for the engine being analyzed.

- Line 19 shows the sound pressure level (SPL; ref. 20 μPa) of the noise transmitted through the tube at angles of 30, 60, 90, and 120 degrees off-axis, at a distance of 250 feet from the engine. The angles on line 19 are rotated 180 degrees from the downstream sense (they are referenced from the axis, looking upstream).

- The remaining seven lines of SPLOUT present additional sound pressure levels calculated using TCNOISE; all SPLs are FLAT, that is, they are unfiltered. To obtain an approximation for dBA (SPL on the A-scale), substract 22 dB from dB FLAT. The last

four lines of the output list the SPLs at the usual microphone locations, allowing direct comparison with measured noise levels.

ACCURACY OF THE PROGRAM

The accuracy of TCNOISE was assessed by comparing predicted noise emissions with SPLs measured at NAS Cubi Point (Schmidt, 1987) and NAS Lemoore (Glass, 1985). Polar graphs making the comparisons are presented as Figures 1 through 4 when the J52 (Mil) and the TF30 (both Mil and A/B) were tested in the T-10 test cell at NAS Cubi Point and the F404 (A/B) was being tested in Test Cell No. 3 at NAS Lemoore. Differences between the calculated SPLs and measured values were typically near 1 dB, with some exceptions to 3 dB. The comparisons are summarized in Table 1. Also included in Table 1, in anticipation of the arrival of an F-18E/F Super Hornet squadron, are noise emissions predicted by TCNOISE when an afterburning F414 engine is tested in Test Cell No. 3 at NAS Lemoore.

Table 1. Comparisons of Noise Emissions Predicted by TCNOISE and Measured at NAS Cubi Point and NAS Lemoore (predicted/measured noise in dBA 250 feet from the engine nozzle; 180 degrees is directly behind the test cell)

Location	Engine	Power	180 deg	150 deg	120 deg	90 deg
NAS Cubi Point	J52	Military	79.5/77.5	74./73.4	67/68.7	65/66.7
	TF30	Military	84.3/81.1	78.8/77.9	71.8/70.4	69.8/70
	TF30	A/B	96.5/96.5	91/88.7	84/85.1	82/80.4
NAS Lemoore	F404	A/B	92.8/94	90.5/88	86.9/88	86.2/87
	F414	A/B	98.8/	96.5/	92.9/	92.2/

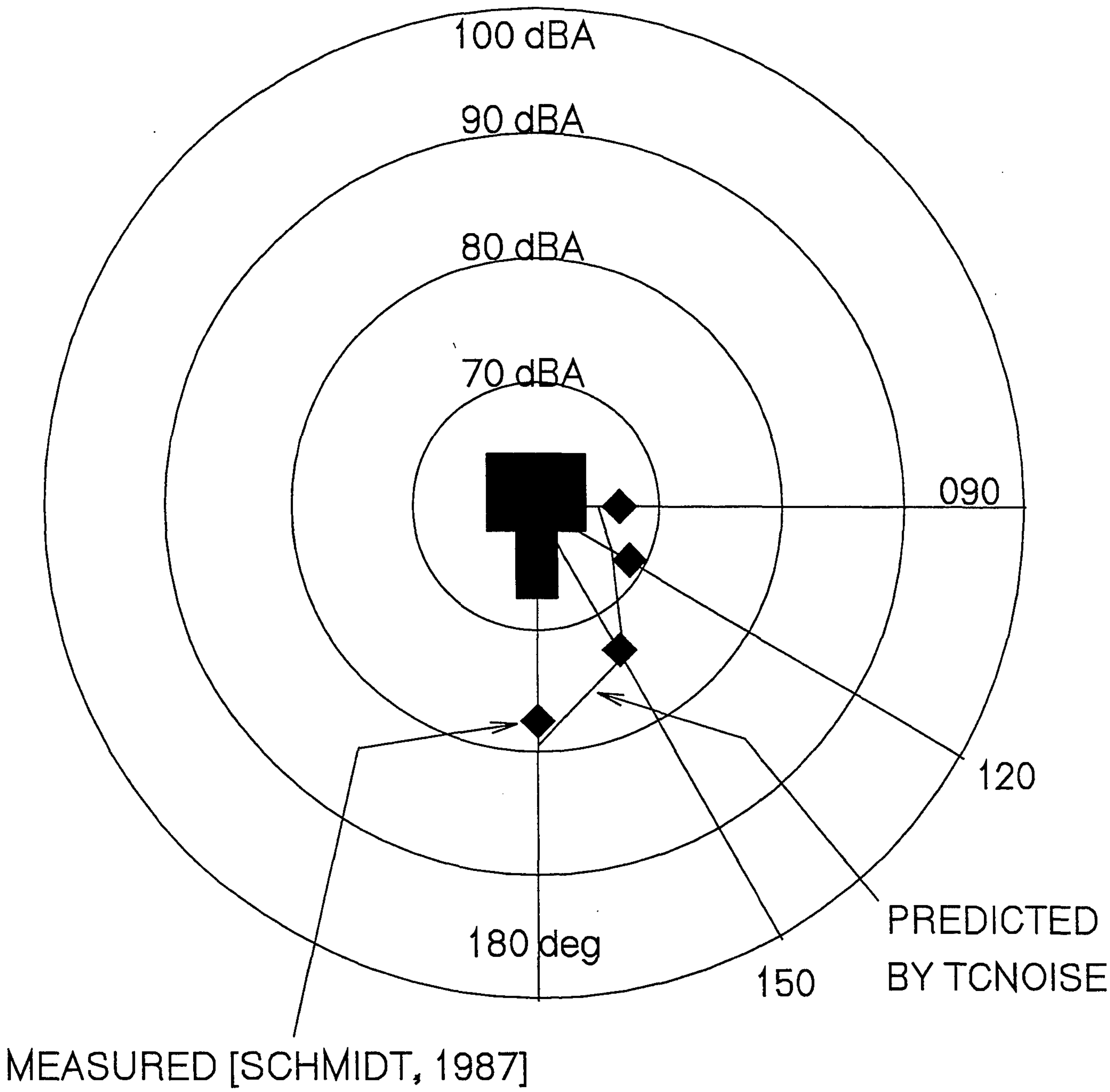

Figure 1
Comparison of T-10 test cell noise emissions predicted by TCNOISE with measured values when running a J52 at Mil power (noise in dBA 250 feet from engine nozzle).

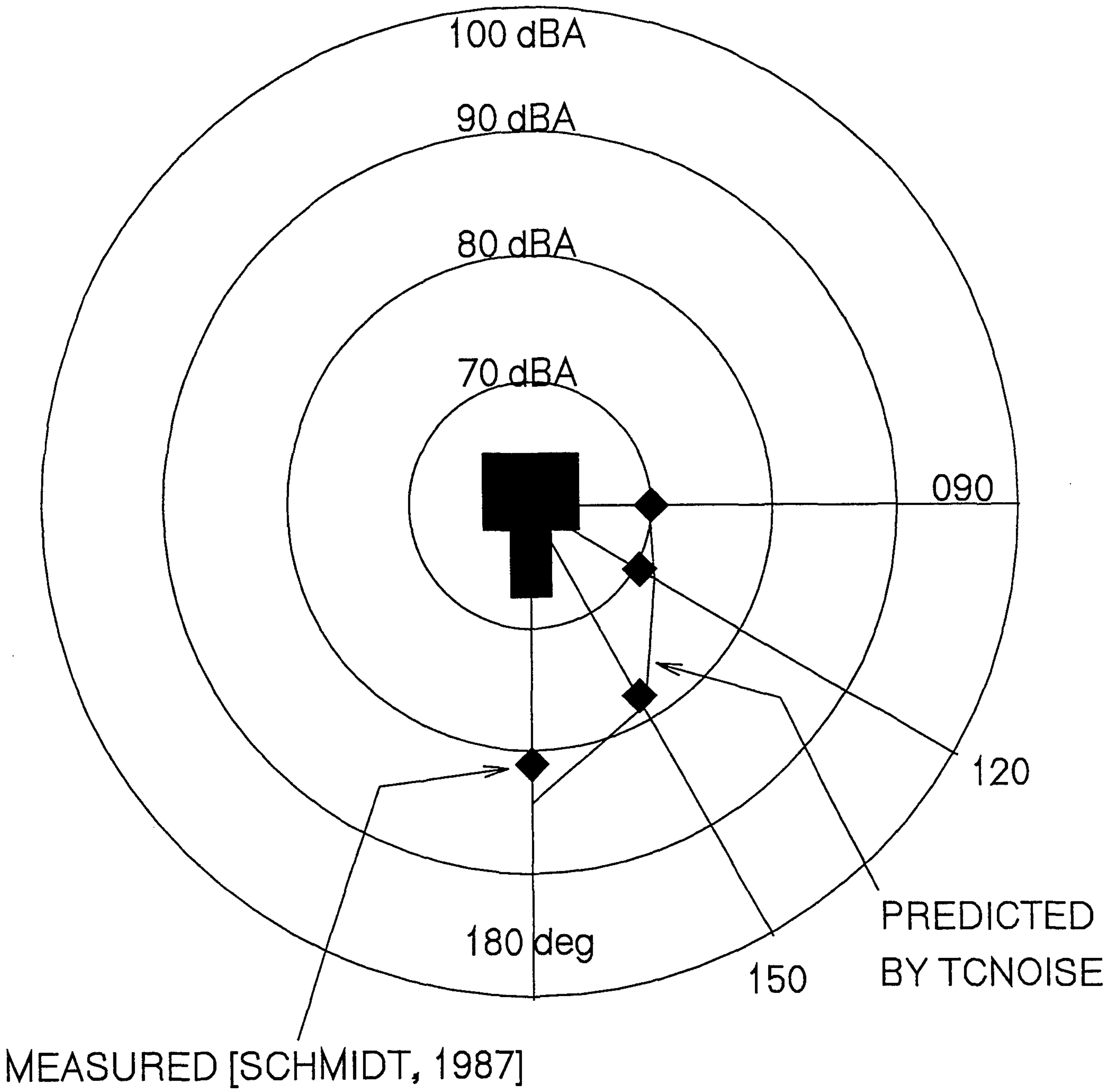

Figure 2
Comparison of T-10 test cell noise emissions predicted by TCNOISE with measured values when running a TF30 at Mil power (noise in dBA 250 feet from engine nozzle).

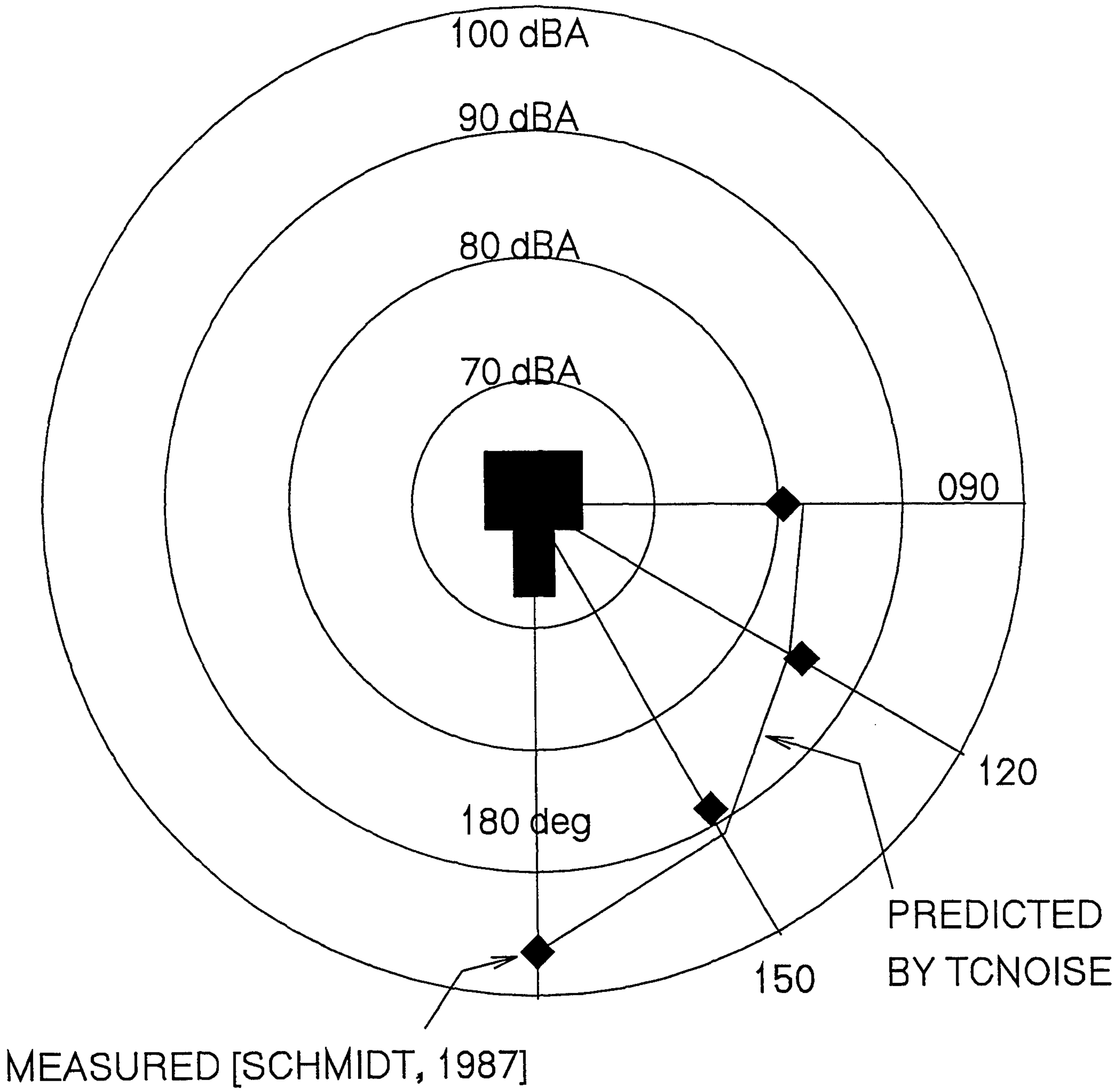

Figure 3
Comparison of T-10 test cell noise emissions predicted by TCNOISE with measured values when running an afterburning TF30 (noise in dBA 250 feet from engine nozzle).

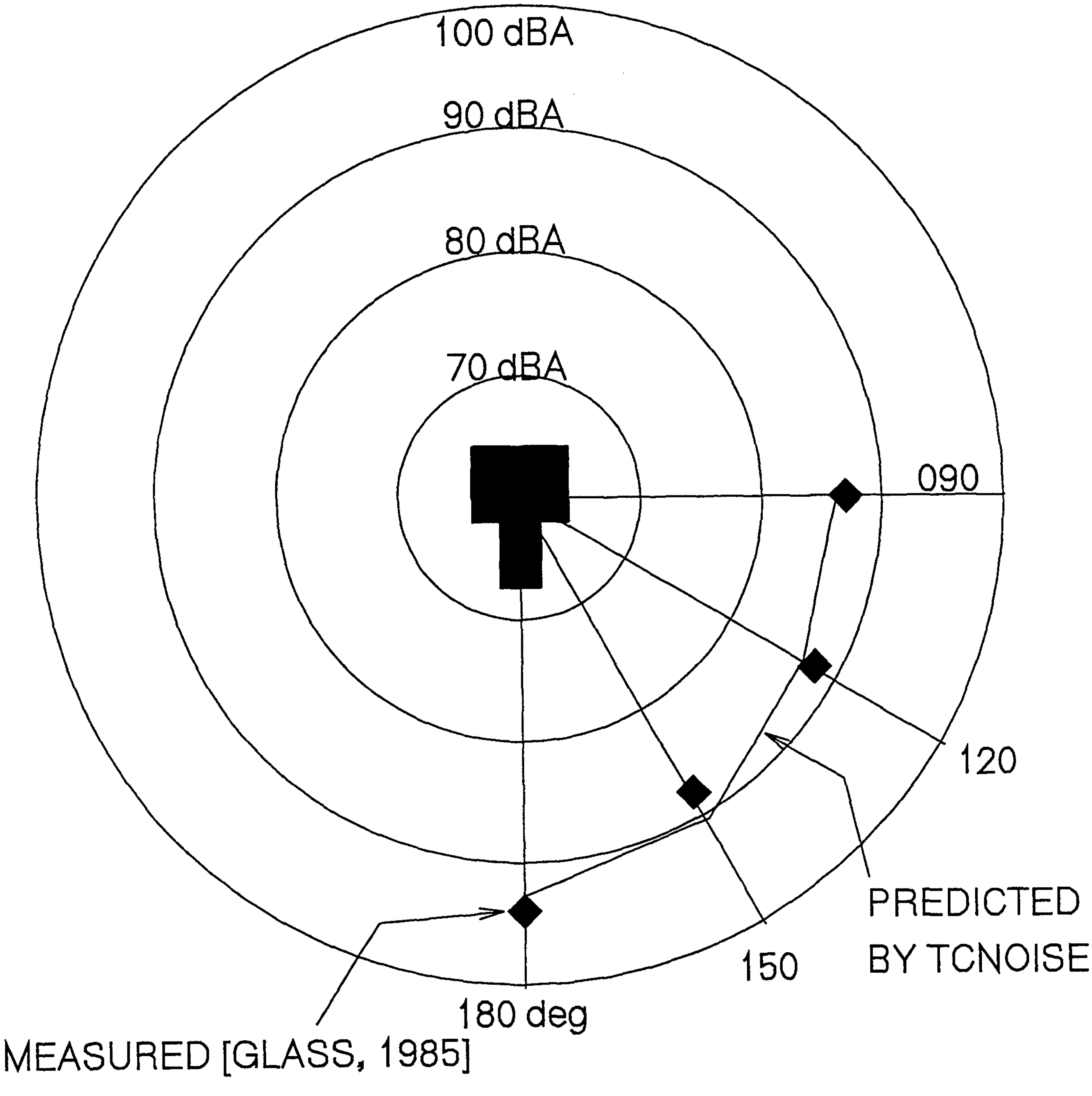

Figure 4
Comparing predicted and measured noise emissions from JETC No. 3 at NAS Lemoore when running an afterburning F404 (noise in dBA 250 feet from engine nozzle).

EXAMPLE RUNS

Two example runs are provided to further illustrate the use of TCNOISE. The first example is the TF30 being tested at military power in the T-10 Test Cell at NAS Cubi Point:

1. The output files from the aerothermal model were given the file name TF30MIL. Segments from these files are included as Tables 2 and 3. Therefore:

```
COPY TF30MIL.JET NOISE.JET
COPY TF30MIL.WAL NOISE.WAL
```

2. Type TCNOISE to run the compiled version of the program.

3. The following inputs are in response to the prompts:

```
4.175
5.5
24.63
14
1.52
30
```

The output file, always called SPLOUT, is included as Table 4. Noise emissions when testing an engine at military power or lower are not a problem. Predicted noise levels in this example are much lower than the design limit of 90 dBA (CFR, 1995) measured at a distance of 250 feet from the engine.

The second example is an afterburning F414 engine being tested in Test Cell No. 3 at NAS Lemoore. As mentioned above, this engine has never been tested in this facility, but its arrival is anticipated shortly, and it would be desirable to know if there will be any noise problems.

1. The output files from the aerothermal model were given the file name F414AB. Segments from these files are included as Tables 5 and 6. Therefore:

```
COPY F414AB.JET NOISE.JET
COPY F414AB.WAL NOISE.WAL
```

2. Type TCNOISE to run the compiled version of the program.

Table 2. Input File NOISE.JET Used to Predict Noise Emissions from the T-10 Test Cell at NAS Cubi Point While Testing a TF30 Engine at Military Power

VEL (m/sec)	TEMP (degK)	DENSITY (kg/m**3)	TURB KE (m/sec)**2	I	J	K
12.7	293.0	1.1865	0.853E+00	3	2	35
18.0	293.0	1.1848	0.130E+01	4	2	35
21.3	293.1	1.1839	0.158E+01	5	2	35
21.4	295.7	1.1742	0.149E+01	6	2	35
18.3	293.0	1.1845	0.133E+01	7	2	35
...	...	...	...			
14.2	293.0	1.1878	0.322E-01	8	3	35
13.6	293.1	1.1871	0.833E+02	3	4	35
21.3	312.1	1.1128	0.808E+04	4	4	35
716.2	837.8	0.4078	0.136E+04	5	4	35
616.3	721.8	0.5006	0.487E+03	6	4	35
19.9	292.3	1.1833	0.596E+03	7	4	35
14.2	293.0	1.1875	0.332E-02	8	4	35
13.0	293.3	1.1865	0.198E+03	3	5	35
18.1	326.9	1.0645	0.633E+04	4	5	35
607.5	721.9	0.5023	0.514E+03	5	5	35
584.1	712.6	0.5261	0.196E+03	6	5	35
19.3	293.0	1.1806	0.143E-03	7	5	35
13.8	293.0	1.1869	0.171E-04	8	5	35
...	...	...	...			
18.8	293.0	1.1835	0.161E+01	7	2	36
12.8	293.0	1.1858	0.120E+01	8	2	36
13.7	293.0	1.1838	0.428E+01	3	3	36
21.6	297.6	1.1642	0.195E+04	4	3	36
36.0	303.8	1.1377	0.126E+05	5	3	36
45.8	317.2	1.0909	0.892E+04	6	3	36
15.9	287.7	1.2038	0.959E+03	7	3	36
15.2	293.0	1.1844	0.256E+00	8	3	36
15.9	293.1	1.1828	0.295E+02	3	4	36
23.2	304.7	1.1359	0.808E+04	4	4	36
617.6	713.4	0.4683	0.308E+04	5	4	36
498.3	600.8	0.5667	0.112E+04	6	4	36
...	...	...	...			
74.9	316.4	1.0677	0.727E+03	8	7	50

Table 3. Input File NOISE.WAL Used to Predict Noise Emissions from the T-10 Test Cell At NAS Cubi Point While Testing a TF30 Engine at Military Power

VEL (m/sec)	TEMP (degK)	DENSITY (kg/m**3)	TURB KE (m/sec)**2	I	J	K
-1.0	321.5	1.0354	0.487E+01	2	1	46
40.5	314.4	1.0565	0.596E+01	3	1	46
44.6	316.3	1.0509	0.284E+01	4	1	46
39.6	323.5	1.0287	0.136E+01	5	1	46
33.1	312.8	1.0644	0.228E+01	6	1	46
40.0	315.4	1.0544	0.464E+01	7	1	46
36.5	319.5	1.0389	0.831E+01	8	1	46
-25.1	324.3	1.0264	0.532E+01	9	1	46
...	...	...	...			
29.5	317.2	1.0485	0.999E+00	2	1	47
53.6	313.5	1.0692	0.136E+03	3	1	47
59.2	318.5	1.0581	0.280E+03	4	1	47
55.9	324.3	1.0411	0.273E+03	5	1	47
49.7	314.8	1.0723	0.261E+03	6	1	47
55.0	316.3	1.0657	0.163E+03	7	1	47
51.6	319.3	1.0504	0.418E+02	8	1	47
23.7	324.1	1.0291	0.183E+01	9	1	47
17.9	308.8	1.0758	0.689E+00	2	8	47
43.6	308.8	1.0843	0.704E+01	3	8	47
45.9	313.5	1.0719	0.663E+01	4	8	47
35.5	315.8	1.0636	0.357E+01	5	8	47
15.0	311.7	1.0771	0.541E+00	6	8	47
-15.9	314.9	1.0665	0.775E+00	7	8	47
-15.8	315.9	1.0635	0.509E+00	8	8	47
-23.7	318.3	1.0528	0.183E+01	9	8	47
...	...	...	...			
-18.7	316.4	1.0638	0.138E+01	7	8	48
-27.1	320.9	1.0492	0.247E+01	8	8	48
-32.7	323.6	1.0383	0.404E+01	9	8	48
40.1	316.7	1.0578	0.770E+01	2	1	49
60.4	317.5	1.0584	0.569E+03	3	1	49
68.0	322.9	1.0424	0.752E+03	4	1	49
65.9	325.0	1.0367	0.742E+03	5	1	49
...	...	...	...			
44.9	352.5	1.0064	0.734E+01	9	8	75

Table 4. Output File SPLOUT from TCNOISE When Used to Predict Noise Emissions from the T-10 Test Cell At NAS Cubi Point When Testing the TF30 Engine at Military Power

k= 1 Jet Noise Power= 137976. Watts
k= 2 Jet Noise Power= 34019. Watts
k= 3 Jet Noise Power= 16504. Watts
k= 4 Jet Noise Power= 9558. Watts
k= 5 Jet Noise Power= 5761. Watts
k= 6 Jet Noise Power= 3873. Watts
k= 7 Jet Noise Power= 3678. Watts
k= 8 Jet Noise Power= 3460. Watts
k= 9 Jet Noise Power= 3083. Watts
k= 10 Jet Noise Power= 2677. Watts
k= 11 Jet Noise Power= 2254. Watts
k= 12 Jet Noise Power= 1387. Watts
k= 13 Jet Noise Power= 853. Watts
k= 14 Jet Noise Power= 536. Watts
k= 15 Jet Noise Power= 342. Watts
k= 16 Jet Noise Power= 219. Watts

EMPIRICAL EQUATION NOISE= 3626056. Watts (TF30,A/B)
Sum of jet noise from nodes = 226187.Watts

NOISE THROUGH PIPE 150,120,90,60 = 71.69 69.40 67.39 61.40 dB @ 250'

Jet noise source field,augmenter tube exit= 137.966 dB
Surface noise field,augmenter tube exit= 129.077 dB
Reverberation field intensity level,IL= 142.982 dB

SPL,180DEG,250FT= 106.277 dB FLAT
SPL,150DEG,250FT= 100.777 dB FLAT
SPL,120DEG,250FT= 93.777 dB FLAT
SPL, 90DEG,250FT= 91.777 dB FLAT
For approximate dBA, subtract 22 dB from dB FLAT.

Program by T.W. Lancey at NFESC, 5/97 - 7/97.

Table 5. Input File NOISE.JET Used to Predict Noise Emissions from NAS Lemoore Test Cell No. 3 While Testing an Afterburning F414 Engine

VEL (m/sec)	TEMP (degK)	DENSITY (kg/m**3)	TURB KE (m/sec)**2	I	J	K
9.5	293.0	1.1862	0.735E+00	3	2	35
13.6	293.0	1.1852	0.104E+01	4	2	35
16.2	293.0	1.1842	0.108E+01	5	2	35
15.9	293.0	1.1844	0.103E+01	6	2	35
14.4	293.0	1.1847	0.114E+01	7	2	35
10.0	293.0	1.1861	0.788E+00	8	2	35
9.8	293.0	1.1853	0.157E+03	3	3	35
24.8	297.6	1.1654	0.238E+04	4	3	35
45.6	316.8	1.0924	0.188E+05	5	3	35
62.1	362.6	0.9540	0.137E+05	6	3	35
22.7	276.7	1.2524	0.308E+04	7	3	35
10.8	293.0	1.1851	0.237E+03	8	3	35
9.5	293.3	1.1840	0.751E+03	3	4	35
47.3	326.5	1.0600	0.148E+05	4	4	35
1101.6	1999.0	0.1721	0.336E+04	5	4	35
940.7	1696.2	0.2104	0.467E+04	6	4	35
23.9	288.4	1.1968	0.143E+05	7	4	35
10.4	293.0	1.1852	0.937E+03	8	4	35
9.1	293.4	1.1838	0.689E+03	3	5	35
54.2	347.5	0.9972	0.120E+05	4	5	35
...	...	...	...			
10.6	293.1	1.1855	0.116E+01	3	2	36
15.5	293.0	1.1847	0.143E+01	4	2	36
18.6	293.0	1.1839	0.132E+01	5	2	36
18.7	293.0	1.1840	0.132E+01	6	2	36
16.2	293.0	1.1842	0.152E+01	7	2	36
12.1	292.9	1.1859	0.139E+01	8	2	36
11.3	293.7	1.1824	0.311E+03	3	3	36
35.8	310.0	1.1181	0.519E+04	4	3	36
71.5	350.3	0.9874	0.246E+05	5	3	36
90.0	403.6	0.8574	0.187E+05	6	3	36
...	...	...	...			
...	...	...	...			
79.7	582.7	0.6335	0.426E+04	8	7	50

Table 6. Input File NOISE.WAL Used to Predict Noise Emissions from NAS Lemoore Test Cell No. 3 While Testing an Afterburning F414 Engine

VEL (m/sec)	TEMP (degK)	DENSITY (kg/m**3)	TURB KE (m/sec)**2	I	J	K
-21.3	518.6	0.6847	0.351E+01	2	1	42
40.3	467.3	0.7589	0.392E+04	3	1	42
51.1	458.5	0.7747	0.487E+04	4	1	42
55.6	453.1	0.7846	0.536E+04	5	1	42
53.9	445.2	0.7987	0.528E+04	6	1	42
47.8	438.4	0.8103	0.472E+04	7	1	42
40.5	435.3	0.8149	0.385E+04	8	1	42
14.8	475.5	0.7462	0.170E+01	9	1	42
-109.5	578.8	0.6097	0.455E+02	2	8	42
-111.1	596.9	0.5918	0.394E+02	3	8	42
-105.3	585.7	0.6038	0.347E+02	4	8	42
-90.4	561.6	0.6290	0.251E+02	5	8	42
...	...	...	...			
54.0	451.2	0.7913	0.402E+04	8	1	43
23.9	476.7	0.7495	0.285E+01	9	1	43
-112.7	578.8	0.6118	0.567E+02	2	8	43
-111.6	598.7	0.5908	0.502E+02	3	8	43
-106.2	587.4	0.6021	0.439E+02	4	8	43
-92.8	565.2	0.6251	0.336E+02	5	8	43
...	...	...	...			
17.4	478.1	0.7502	0.542E+04	5	1	44
75.2	472.5	0.7596	0.531E+04	6	1	44
70.4	468.1	0.7669	0.483E+04	7	1	44
64.7	466.8	0.7689	0.410E+04	8	1	44
...	...	...	...			
-111.4	582.6	0.6119	0.577E+02	2	8	44
-102.6	601.1	0.5922	0.467E+02	3	8	44
-98.8	592.8	0.6001	0.418E+02	4	8	44
-87.2	576.1	0.6173	0.332E+02	5	8	44
...	...	...	...			
83.9	493.9	0.7295	0.506E+04	4	1	45
84.3	490.0	0.7359	0.532E+04	5	1	45
82.2	485.3	0.7433	0.520E+04	6	1	45
78.3	481.8	0.7488	0.477E+04	7	1	45
...	...	...	...			
11.3	584.3	0.6503	0.506E+01	9	8	66

3. The following inputs are in response to the prompts:

3.048
5.5
18.3
10
2.2
25

The output file is included as Table 7. This will be a noisy test. As shown on Table 1, the relatively small Test Cell No. 3 at NAS Lemoore, when testing the afterburning F414, is more than 2 dB noisier than the standard T-10 when testing an afterburning TF30 engine.

SOME PARAMETRIC ANALYSES

TCNOISE is coupled to the aerothermal model to the extent that most changes to the geometry of the test cell that affect noise emissions affect these emissions by changing the aerothermal performance of the facility; for example, changing velocities and turbulence. Therefore, for new test cells and for most major changes in the design of an existing facility, accurate input files, NOISE.JET and NOISE.WAL, must be generated before running TCNOISE. The program, by itself, is certainly of value in assessing trends (most are already well known qualitatively but not quantitatively) and may be used, with some discretion, as a design tool for predicting noise emissions, varying the dimensions of the facility.

Several test cell dimensions have only a minor influence on the aerothermal performance of the facility: the augmenter shell diameter, the length of the tube, and the height of the exhaust stack. Table 8 compares the effects of changing each of these parameters, assuming an afterburning F414 engine is being run in Test Cell No. 3 at NAS Lemoore. Of these parameters, the effect of increasing the height of the exhaust stack is the most pronounced, decreasing the far field noise by about 7 dB when increased to the height of the intake stack.

Switching from a round augmenter tube to a rectangular tube in the Navy's T-10 jet engine test cell design is expected to save $540K on the construction costs of each new facility (Ference, 1995). Based on aerothermal performance predicted by the NFESC test cell model, both the 13.7-foot (4.17-meter) square and 9x15-foot (2.7x4.6-meter) rectangular augmenter tube configurations are acceptable alternatives to the current 13.7-foot diameter round tube (Kodres, 1996). The effects of these tube modifications on test cell noise emissions are another factor that will influence the switch. With this in mind, TCNOISE is used to predict noise generation in a T-10 test cell constructed with each of the potential replacement augmenter tubes. An afterburning TF30 engine is being tested. The results are summarized in Table 9.

Table 7. Output File SPLOUT from TCNOISE When Used to Predict Noise Emissions from NAS Lemoore Test Cell No. 3 When Running an Afterburning F414 Engine

```
k= 1  Jet Noise Power=  4339071. Watts
k= 2  Jet Noise Power=  1705316. Watts
k= 3  Jet Noise Power=   658610. Watts
k= 4  Jet Noise Power=   299424. Watts
k= 5  Jet Noise Power=   292062. Watts
k= 6  Jet Noise Power=   329762. Watts
k= 7  Jet Noise Power=   106347. Watts
k= 8  Jet Noise Power=    29552. Watts
k= 9  Jet Noise Power=     8828. Watts
k= 10  Jet Noise Power=    2838. Watts
k= 11  Jet Noise Power=     980. Watts
k= 12  Jet Noise Power=     369. Watts
k= 13  Jet Noise Power=     152. Watts
k= 14  Jet Noise Power=      67. Watts
k= 15  Jet Noise Power=      32. Watts
k= 16  Jet Noise Power=      16. Watts

EMPIRICAL EQUATION NOISE= 3626056. Watts (TF30,A/B)
Sum of jet noise from nodes = 7773435. Watts

NOISE THROUGH PIPE 150,120,90,60 = 87.05  84.76  82.75  76.76 dB @ 250'

Jet noise source field,augmenter tube exit= 153.327 dB
Surface noise field,augmenter tube exit= 129.338 dB
Reverberation field intensity level, IL= 160.620 dB

SPL,180DEG,250FT=  120.768 dB FLAT
SPL,150DEG,250FT=  118.468 dB FLAT
SPL,120DEG,250FT=  114.868 dB FLAT
SPL, 90DEG,250FT=  114.168 dB FLAT
For approximate dBA, subtract 22 dB from dB FLAT.

Program by T.W. Lancey at NFESC, 5/97 - 7/97.
```

Table 8. Effects of Test Cell Modifications on Noise Emissions Predicted by TCNOISE When Running an Afterburning F414 Engine in Test Cell No. 3 at NAS Lemoore (predicted noise in dBA 250 feet from the engine nozzle; 180 degrees is directly behind the test cell)

Modification	180 deg	150 deg	120 deg	90 deg
Existing Configuration	98.8	96.5	92.9	92.2
Incr. Aug. Shell Diameter by 1 m.	98.2	95.9	92.3	91.6
Incr. Aug. Length by 6 m.	98.7	96.4	92.8	92.1
Incr. Exh. Stack Height by 4 m.	91.4	89.1	85.5	84.8

Table 9. Effects of T-10 Test Cell Augmenter Tube Modifications on Noise Emissions When Running an Afterburning TF30 Engine (predicted noise in dBA 250 feet from the engine nozzle; 180 degrees is directly behind the test cell)

Modification	180 deg	150 deg	120 deg	90 deg
Standard T-10 Test Cell	96.5	91	84	82
T-10 JETC with 13.7-ft Square Tube	97	91.5	84.5	82.5
T-10 with 9x15-ft Rectangular Tube	97	94.7	91.1	90.4
T-10 with Square Tube, no Secondary	94.6	89.1	82.1	80.1

The T-10 configuration with a 13.7-foot. square augmenter tube is about 0.5 dB noisier than the standard T-10. This is somewhat of a surprise. Tube gas velocities and generated turbulence are lower (Kodres, 1996) through the square augmenter tube because of the larger cross-sectional area. However, the square tube configuration was assumed to have no transition section to smooth out the flow at the beginning of the augmenter tube. The jet noise is approximately 13 percent greater.

Switching to a 9x15-foot rectangular augmenter tube will result in a much noisier test cell. Gas velocities and turbulence are greater through the smaller cross section of the tube. Again, this configuration was assumed to have no transition section.

Eliminating the secondary inlet decreases the mass flows through the facility and, as a result, greatly decreases the noise emissions.

ACKNOWLEDGMENTS

The development of TCNOISE was funded by the Pollution Abatement Ashore Program, managed by the Naval Facilities Engineering Command, and sponsored by the Environmental Protection, Safety and Occupational Health Division (N45) of the Chief of Naval Operations.

REFERENCES

CFR (Code of Federal Regulations) (1995). Title 40, Protection of environment, Part 60.44b, Office of the Federal Register, Washington, DC, 1995.

Ference, E. (1995). Next generation jet engine test cell improvement criteria, Naval Facilities Engineering Command, Contract Report. Pacific Environmental Services, Norfolk, VA, 1995.

Ffowcs Williams, J.E. (1972). "The acoustics of turbulence near sound absorbent liners," Journal of Fluid Mechanics, vol 51, 1972, pp. 737-749.

Glass, R.E. (1985). Noise levels of the NAS Lemoore round augment test cell (no. 3) during TF30, F404 and TF41 engine operation, Naval Ocean Systems Center, Technical Document 836. San Diego, CA, 1985.

Jones, I.S.F. (1965). "Aerodynamic noise dependent on mean shear," Journal of Fluid Mechanics, vol 33, no. 1, 1965.

Kinsler, L.E. and A.R. Frey (1962). Fundamentals of acoustics. 2nd Ed., New York, NY, Wiley & Sons, 1962, p 171.

Kodres, C.A. and G.L. Murphy (1996). Aerothermal performance of the Navy T-10 jet engine test cell when constructed with a rectangular augmenter tube, Naval Facilities Engineering Service Center, Technical Memorandum TM-2236-ENV. Port Hueneme, CA, 1996.

Lahey Computer Systems, Inc. (1995). Fortran 90 user's guide, Revision D. Incline Village, NV, 1995.

Lush, P.A. (1971). "Measurements of subsonic jet noise and comparison with theory," Journal of Fluid Mechanics, vol 44, no. 3, 1971.

MacGregor, G.R., H.S. Ribner, and H. Lam (1973). "Basic jet noise patterns after deletion of convection and refraction effects: experiments vs. theory," Journal of Sound and Vibration, vol 27, no. 4, 1973, pp 437-454.

Morris, P.J., W. Richarz, and H.S. Ribner (1973). "Reduction of peak jet noise using jet refraction," Journal of Sound and Vibration, vol 29, no. 4, 1973, pp 443-455.

Nelson, P.A. (1982). "Noise generated by flow over perforated surfaces," Journal of Sound and Vibration, vol 83, no. 1, 1982.

Schmidt, D.R. (1987). Noise levels of the NAS Cubi Point, WRAP., T10 test cell during J52, J52/P408, F404, TF30/P414 and TF41 engine runups, Naval Ocean Systems Center, Technical Note 1501. San Diego, CA, 1987.

Spalding, D.B., et al. (1996). The PHOENICS reference manual, CHAM Technical Report TR200. CHAM Ltd., London, England, 1996.

Wilson, C.E. (1989). Noise control. New York, NY, Harper & Row, NY, 1989, pp 77, 339.

APPENDIX

FORTRAN LISTING OF TCNOISE

```
      PROGRAM TCNOISE
C  Program to calculate noise emissions from jet engine test cells or
C  hush houses...used in conjunction with the Naval Facility Engineering
C  Service Center's test cell aerothermal model....
C  Developed by Timothy W. Lancey at the NFESC, Port Hueneme, CA.
C  Date of this version:  1 Jul 1997
C
C  Dimension arrays for jet velocity, density, temperature and turbulence
C  intensity.
      REAL, DIMENSION(10,10,120) :: U,RHO1,TMP1,XKE,X,Y
      REAL, DIMENSION(60) :: Prprtion,EngnNois
      COMMON U,RHO1,TMP1,XKE,X,Y,Prprtion,EngnNois
      COMMON DD,AugTubeL,AugShelD,BarrierH,kc
      REAL DD,AugTubeL,AugShelD,BarrierH
      COMMON R,G,GAMMA
C
C  Open the file which contains the U,RHO1,TMP1,XKE input from the
C  aerothermal program.
      PRINT*, "i-node no.@   j-node no@  axial"
      PRINT*, "position k   position k  node k   VELOCITY    DENSITY"
     & ,"    TEMP     TURB INTNS"
       ic=6
       jc=6
       kcount=16
      OPEN (UNIT=1,FILE='NOISE.JET',STATUS='OLD')
      REWIND 1
C  Get file ready to read
      DO 100 k=1,kcount
C  k= axial node locations from jet <60
       DO 100 j=1,jc
C  i= nodes at axial position k , i<20
       DO 100 i=1,ic
       READ(1,500) U(i,j,k),Tmp1(i,j,k),RHO1(i,j,k),xke(i,j,k)
       WRITE(5,510)I,j,k,U(i,j,k),Tmp1(i,j,k),RHO1(i,j,k),xke(i,j,k)
  100  CONTINUE
      PRINT*,"Enter the augmenter tube diameter, in meters: "
      READ*,DD
      PRINT*,"Enter the augmenter shell diameter, in meters: "
      READ*,AugShelD
```

```
      PRINT*,"Enter the augmenter tube length, in meters: "
      READ*,AugTubeL
      PRINT*,"Enter the integer 10 or 14, depending on whether the "
      PRINT*,"augmenter tube diameter is closer to 10 feet or 14 feet: "
      READ*,MTubeDia
      PRINT*,"Enter the vertical distance from the augmenter tube to "
      PRINT*, "the top of the ramp, in meters: "
      READ*,BarrierH
      PRINT*,"Enter the number of surface noise nodes in the axial "
      PRINT*, "direction, an integer dictated by the augmenter length: "
      READ*,kc
      PRINT*,"The augmenter tube diameter= " ,DD," meters."
      PRINT*,"The augmenter tube length= " ,AugTubeL," meters."
      PRINT*,"The augmenter shell diameter= " ,AugShelD," meters."
      PRINT*,"The aug tube to ramp barrier height= ",BarrierH," meters."
      WRITE(5,504)kc
C
C specific heat ratio
      gamma=1.3
C the acceleration of gravity in meters/second^2
      g=9.80665
C and gas constant for air in meter*Newton/Kg*Kelvin
      R=286.996
C Write to SPLOUT
      OPEN (UNIT=9,FILE='SPLOUT',STATUS='REPLACE')
C
      CALL JETNOISE(GAMMA,G,R,AUGjet,DD,AugTubeL,AugShelD,SUMJET)
      CALL SURFNOISE(GAMMA,G,R,AUGSURF,DD,AugTubeL,AugShelD,kc,WSURF)
C At the augmenter tube exit, the source noise from the jet combines
C with the reverberant field and the surface noise.
      CALL REVERB(SUMJET,WSURF,DD,AugTubeL,AugShelD,AUGREVRB)
C
      PRINT*,"Jet noise source field,augmenter tube exit=",AUGJET
      PRINT*,"Surface noise field,augmenter tube exit=",AUGSURF,"dB"
      PRINT*, "Reverberation field intensity level,IL=",augrevrb," dB"
      ABAR=SQRT(6.1**2+BARRIERH**2)
C Ref: C.E.Wilson"NOISE CONTROL" P77-79
        AXISL=76.2-AugTubeL
C from aug tube to 250 feet.
        RAMP250=AXISL-6.1
C ramp to 250 feet
        BBAR=SQRT(RAMP250**2+BARRIERH**2)
        FRESNEL=2.0*125.0*(ABAR+BBAR-AXISL)/343.0
C Fresnel No. at 125 Hz
C Celerity C=343M/SEC
```

```
        FRSNLARG=SQRT(6.28*FRESNEL)
C  SQRT(2*PI*Fresnel No.)
        e1=EXP(FRSNLARG)
        HYPTan=(e1-(1.0/e1))/(e1+(1.0/e1))
        dIL=5.0+20.0*LOG10(FRSNLARG/HYPTan)
      PRINT*,"BARRIER ATTENUATION DUE TO DIFFRACTION=",dIL
      PRINT*,"DD,AugTubeL,AugShelD=",DD,AugTubeL,AugShelD
      XPREVERB=AUGREVRB/10.0
      XPJETSRC=AUGJET/10.0
      SUMNOIS=(10.0**XPREVERB)+(10.0**XPJETSRC)
      SUMLOGIL=10.0*LOG10(SUMNOIS)
      SPL250180=SUMLOGIL-(dIL)-20.0*LOG10(AXISL/1.524)
C  noise at exit of augmenter tube - barrier diffraction - spherical
C  expansion to 250 feet.
      IF (MTubeDia==10) THEN
       SPL250150=SPL250180-2.3
C  Using radiation from baffled piston
       SPL250120=SPL250180-5.9
C  of radius=a, with lamda=2.74a.
         SPL25090=SPL250180-6.6
         GO TO 111
      END IF
      SPL250150=SPL250180-5.5
C  Using radiation from baffled piston,
      SPL250120=SPL250180-12.5
C  of radius=a, with lamda=2a.
      SPL25090=SPL250180-14.5
 111  PRINT*, "SPL,180DEG,250FT=",SPL250180,"dB FLAT"
      PRINT*, "SPL,150DEG,250FT=",SPL250150,"dB FLAT"
      PRINT*, "SPL,120DEG,250FT=",SPL250120,"dB FLAT"
      PRINT*, "SPL,90DEG,250FT=",SPL25090,"dB FLAT"
      PRINT*,"For approximate dBA, subtract 22 dB from dB FLAT."
      WRITE(9,460)AUGJET
      WRITE(9,465)AUGSURF
      WRITE(9,470)AUGREVRB
      WRITE(9,475)SPL250180
      WRITE(9,480)SPL250150
      WRITE(9,485)SPL250120
      WRITE(9,490)SPL25090
      WRITE(9,492)
      WRITE(9,493)
 460  FORMAT("Jet noise source field,augmenter tube exit=",F8.3," dB")
 465  FORMAT("Surface noise field,augmenter tube exit=",F8.3," dB")
 470  FORMAT("Reverberation field intensity level,IL=",F8.3," dB")
 475  FORMAT("SPL,180DEG,250FT=",F9.3," dB FLAT")
```

```
480 FORMAT("SPL,150DEG,250FT=",F9.3," dB FLAT")
485 FORMAT("SPL,120DEG,250FT=",F9.3," dB FLAT")
490 FORMAT("SPL, 90DEG,250FT=",F9.3," dB FLAT")
492 FORMAT("For approximate dBA, subtract 22 dB from dB FLAT.")
493 FORMAT("Program by T.W. Lancey at NFESC, 5/97 - 7/97.")
500 FORMAT(2F10.1,F10.4,E13.3)
504 FORMAT("Number of axial surface noise nodes=",I3)
510 FORMAT(5X,I3,5X,I3,5x,I3,8X,F8.3,3X,F8.3,3X,F8.3,3x,E14.3)
520 FORMAT(5X,I3,8X,I3,8X,F8.3)
    STOP
    END
C
    SUBROUTINE JETNOISE(GAMMA,G,R,AUGjet,DD,AugTubeL,AugShelD,SUMJET)
    COMMON U,RHO1,Tmp1,XKE,X,Y,Prprtion,EngnNois
C  Calculate jet noise power using Lighthill's Eqn & empirical factor
    REAL DD,AugTubeL,AugShelD
    REAL JETD,Xjnois,d2,A,FacMach,vj,r,EmprNois
    REAL, DIMENSION(120) :: NodJNois,EngnNois,PrPrtion
    REAL, DIMENSION(10,10,120) :: RHO1,U,TMP1,XKE
    EmprNois=0.0
C  the speed of sound at ambient temperature, m/sec
        c1=350.0
C  jet velocity, m/sec
      vj=904.0
C  ambient density, Kg/m^3
        ro=1.203
C  the diameter of the jet nozzle, meters
        jetd=0.942
C  Mc=0.65*vj/c1
      ic=6
      jc=6
      kc=16
     FacMach=1.0
     EmprNois=0.00004*ro*(jetd**2)*(FacMach)*(vj**8)/(c1**5)
    PRINT*, " From Lighthill's empirical equation,Acoustic
   / power of the jet =",EmprNois
     PRINT*, "EMPIRICAL NOISE=",EmprNois
    DO 150 K=1,kc
     NodJNois(k)=0.0
 150 CONTINUE
     SumJet=0.0
     DO 220 k=1,kc
C  calc noise at axial location k, with
C  k=1 at engine exit plane. Noise from
C  each axial location is found, then
```

```
C  all noise levels are calculated.
      PRINT*, "GAMMA=",GAMMA," G=",G," R=",R
        A=0.00004*ro/((C1)**5)
      DO 200 i=1,ic
      DO 200 j=1,jc
       vj=U(i,j,K)
       FacMach=1.0
         d2=0.1233
         XJnois=A*d2*FacMach*((vj)**8)
       NodJNois(k)=NodJNois(k)+XJNois
      PRINT*, "NodJNois(",k,")=",NodJNois(k)
 200  CONTINUE
         SumJet=SumJet+NodJNois(k)
C  NodJNois is the acoustic power from all of the i,j nodes at the k
C  location from the jet exit plane.
C  SumJet is the sum of the power from all of the k locations.
 220  CONTINUE

cc    !!  * * * * * * *
cc    !!   31        36
cc    !!  * * * * * * *
cc    !!   25        30
cc    !!  * * * * * * * <<<--Mesh pattern for each axial
cc    !!   19  21 22  24      station k.
cc    !!  * * * O * * *
cc    !!   13  15 16  18
cc    !!  * * * * * * *
cc    !!    7        12
cc    !!  * * * * * * *
cc    !!    1 2 3 4 5 6
cc    !!  * * * * * * *

      SUMJET=(1.0)*SUMJET
       PRINT*, "Sum of jet noise from nodes =",SumJet
      DO 224 K=1,kc
       Prprtion(K)=(1.0*NodJNois(k))/SumJet
C  Proportion of noise
C  from each axial location to total jet engine noise
 224 CONTINUE
      DO 230 K=1,kc
        EngnNois(k)=Prprtion(k)*SumJet
C  Corrected jet noise at each axial k location.
     PRINT*, "  k=",K,"  Jet Noise Power=",EngnNois(k)
     WRITE(9,225)k,EngnNois(k)
 225 FORMAT ("k=",I3,"  Jet Noise Power=",F14.4," Watts")
```

```
230  CONTINUE
     PRINT*, "EMPIRICAL EQUATION NOISE=",EmprNois
     WRITE(9,232)EmprNois
     WRITE(9,235)SumJet
232  FORMAT("EMPIRICAL EQUATION NOISE=",F14.4," Watts (TF30,A/B)")
235  FORMAT("Sum of jet noise from nodes =",F14.4,"Watts")
222  FORMAT (F14.4)
C  The source field is modified (1) by the jet radial expansion from
C  approx 1 m to the 18' (5.5 m) outer pipe and (2) by jet refraction
C  and absorption, for a 15.8 dB attenuation, on-axis. Then we need
C  only consider SumJet, and not the individual k contributions.
     PipeSpher=3.1416*4.0*(AugShelD/2.0)**2
C  area of approx 5.5m sphere
      AUGJET=10.0*LOG10((SumJet/PipeSpher)/1.0E-12)-15.8
C  dB at augmenter tube exit for the near 0n-axis noise. The
C  maximum source noise is realized from the 0n-axis component.
C
     PRINT*,"Jet noise source field at augmenter tube exit=", AUGJET
C
C  NOISE AT OUTER PIPE
C
C  Calculate noise at outside of outer pipe - varies along Z -
C  sound from jet expands from D=1 to D=5.5 at wall and varies with angle
C                        (r=2.25 meter)
C  and refraction (also a function of angle). At outside of pipe,
C  PIPONL= EXPANDIL-10dBpillows-1.5dBliner-41dBpipewall+REFRACTION
       PIPINT30=0.0
       PIPINT60=0.0
       PIPINT90=0.0
      DO 260 K=1,kc
        JETSRC=EngnNois(k)/(4.0*3.1416*1.0**2)
C  Watts/M^2
        PIPint30=PIPINT30+jetsrc/((4.5 *2.0)**2)
        PIPINT60=PIPINT60+jetsrc/((4.5/0.866)**2)
        PIPINT90=PIPINT90+JETSRC/((4.5*1.0)**2)
C  Watts/M^2
260  CONTINUE
C  PIPINT120=PIPINT60
        PIPIL30=10.0*LOG10(PIPINT30/1.0E-12)-10.0-1.5-41.0+5.3
        PIPIL60=10.0*LOG10(PIPINT60/1.0E-12)-10.0-1.5-41.0+3.0
        PIPIL90=10.0*LOG10(PIPINT90/1.0E-12)-10.0-1.5-41.0+1.0
        PIPIL120=10.0*LOG10(PIPINT60/1.0E-12)-10.0-1.5-41.0-5.0
        SPL25030=PIPIL30-20.0*LOG10(76.2/4.5)
        SPL25060=PIPIL60-20.0*LOG10(76.2/2.6)
        SPL25090=PIPIL90-20.0*LOG10(76.2/2.25)
```

```
      SPL250120=PIPIL120-20.0*LOG10(76.2/2.6)
     WRITE(9,275)SPL25030,SPL25060,SPL25090,SPL250120
275 FORMAT("NOISE THROUGH PIPE 150,120,90,60 =",4F7.2," dB @ 250'")
C
     PRINT*, "NOISE THROUGH PIPE 30,60,90,120 =",SPL25030,", ",
    /        SPL25060,", ",SPL25090,", ",SPL250120," dB @ 250'"
280 FORMAT("WA=",E12.4," SURFACEW=",E12.4,"  i,j,k,m=",4I2)
285 FORMAT("surfpower=",E12.4," SURFACEW=",E12.4,"  i,j,k,m=",4I2)
290 FORMAT("m=",i3,"**SURFACEW ATAXIALNODE",i3,"=",e12.4," P=",e12.4)
600 FORMAT(12X,F8.3,6X,F8.3,6X,F8.3)
610 FORMAT(5X,I3,8X,I3,8x,I3,8X,F8.3,6X,F8.3,6X,F8.3,6x,F8.3)
620 FORMAT(5X,I3,8X,I3,8X,i3,6x,F12.3)
    END SUBROUTINE JETNOISE
C
    SUBROUTINE SURFNOISE(GAMMA,G,R,AUGSURF,DD,AugTubeL,
   1 AugShelD,kc,WSURF)
    REAL, DIMENSION(10,10,120) :: U,RHO1,TMP1,XKE,SURFPOWER
    COMMON U,RHO1,Tmp1,XKE,X,Y,Prprtion,EngnNois
    REAL DD,AugTubeL,AugShelD
    REAL INTENS,WSURF,SRFP
    REAL, DIMENSION(9) :: F
    DATA DELTAZ/0.6/
    mc=4
    jc=2
    ic=8
    kend=2*kc
    kstart=kc+1
    OPEN (UNIT=2,FILE='NOISE.WAL',STATUS='OLD')
    REWIND 1
C  Get file ready to read
    DO 101 k=1,kc
C  k= axial node locations from jet <60
     DO 101 j=1,jc
C  i= nodes at axial position k , i<20
     DO 101 i=1,ic
      READ(2,360) U(i,j,k),Tmp1(i,j,k),RHO1(i,j,k),xke(i,j,k)
      y=ABS(U(i,j,k))
      IF(Y<0.100) THEN
       U(i,j,k)=0.50
      END IF
 101  CONTINUE
     DO 102 k=kstart,kend
C  k= axial node locations from jet <60
     DO 102 j=1,ic
C  i= nodes at axial position k , i<20
```

```
      DO 102 i=1,jc
       READ(2,360) U(i,j,k),Tmp1(i,j,k),RHO1(i,j,k),xke(i,j,k)
       y=ABS(U(i,j,k))
       IF(Y<0.100) THEN
        U(i,j,k)=0.50
       END IF
 102   CONTINUE
C  Open area ratio,  SI = %0pen/100, D = HOLE DIAMETER
      SI=0.3
      D=0.02
C  calculate total duct area in length DELTAZ
       DUCTA=3.1416*DD*DELTAZ
C  calculate duct cross section area
       CROSSA=0.7854*DD**2
C  mean flow speed nearest augmenter tube end, near ID = U(I,J,K)
C  F(i) = FREQUENCY(Hz)
      DATA F(1),F(2),F(3),F(4)/125.0,250.0,500.0,1000.0/
C  Analyze at 4 frequencies
      WSURF=0.0
      SRFP=0.0
      DO 30 I=1,IC
      DO 30 J=1,JC
      DO 30 K=1,kc
      SURFPOWER(i,j,k)=0.0
C  Initialize array to zero
  30  CONTINUE
      DO 320 m=1,mc
      DO 310 k =1,kC
       SURFACEW=0.0
      DO 300 i = 1,ic
      DO 300 j = 1,jc
       VJ=ABS(U(i,j,k))
       T=TMP1(i,j,k)
C  temperature in degrees kelvin
         TI=SQRT(XKE(i,j,k)/VJ**2.0)
       rho=rho1(i,j,k)
       C=(GAMMA*G*R*T)**0.5
  35  FORMAT("  frequency=", F8.2," Hz")
C  Calculate Strouhal Number based on hole diameter
        ST=F(M)*D/VJ
C  Calculate variable of Struve Function of the first kind
        z=12.56637*ST
C  Find Strouhal No. dependence by use Strouhal & Struve Functions
      ALST=0.0063662*((Z**0.667)-(Z**0.0888)+(Z**0.0038)-(Z**0.000081))
C  Calculate the sound power radiated per unit area
```

```
      WA=RHO*0.322982*((TI**2)*(VJ**6)*ST*ALST)/(SI*C**3)
      WA=ABS(WA)
C  Calculate the sound power radiated
      SURFACEW=SURFACEW+WA
C  Power/Area at each axial location
 300   CONTINUE
C  End i,j loops
     SURFACEW=SURFACEW*DUCTA
C  where DUCTA=PI*(AUG TUBE DIA)*DELTAZ
     SRFP= SRFP+SURFACEW
 310  CONTINUE
C  End of k loop
      SURFPOWER(ic,jc,kc)=SRFP
      WSURF1=SURFPOWER(ic,jc,kc)
C  Total power from nodes near exit
 320  CONTINUE
C  End loop through spectrum
     WSURF=0.0
     SRFP=0.0
     DO 40 I=1,jC
     DO 40 J=1,iC
     DO 40 K=kstart,kend
     SURFPOWER(i,j,k)=0.0
C  Initialize array to zero
  40  CONTINUE
      DO 620 m=1,mc
      DO 610 k =kstart,kend
       SURFACEW=0.0
      DO 600 i = 1,jc
      DO 600 j = 1,ic
       VJ=ABS(U(i,j,k))
       T=TMP1(i,j,k)
C  temperature in degrees kelvin
          TI=SQRT(XKE(i,j,k)/VJ**2.0)
       rho=rho1(i,j,k)
C  TF=9.0*((T-273.0)/5.0)+32.0      !! deg F
       C=(GAMMA*G*R*T)**0.5
C  Calculate Strouhal Number based on hole diameter
        ST=F(M)*D/VJ
C  Calculate variable of Struve Function of the first kind
        z=12.56637*ST
C  Find Strouhal No. dependence by use Strouhal & Struve Functions
      ALST=0.0063662*((Z**0.667)-(Z**0.0888)+(Z**0.0038)-(Z**0.000081))
C  Calculate the sound power radiated per unit area
      WA=RHO*0.322982*((TI**2)*(VJ**6)*ST*ALST)/(SI*C**3)
```

```
      WA=ABS(WA)
C  Calculate the sound power radiated
      SURFACEW=SURFACEW+WA
C  Power/area at each axial location
C
 600  CONTINUE   !!! End i,j loops
     SURFACEW=SURFACEW*DUCTA       !where DUCTA=PI*(aug tube dia)*DELTAZ
     SRFP= SRFP+SURFACEW
 610  CONTINUE
C  End of k loop
       SURFPOWER(ic,jc,kc)=SRFP
       WSURF2=SURFPOWER(ic,jc,kc)
C  Total power from nodes near exit
 620  CONTINUE
C  End loop through spectrum
      WSURF=WSURF1+WSURF2
     PRINT*, "TOTALSURFACENOISE POWER=",WSURF,"WATTS",ic,jc,kc
 340  FORMAT("WA=",E12.4," SURFACEW=",E12.4,"  i,j,k,m=",4I2)
 341  FORMAT("surfpower=",E12.4," SURFACEW=",E12.4,"  i,j,k,m=",4I2)
 641  FORMAT("surfpower=",E12.4," SURFACEW=",E12.4,"  i,j,k,m=",4I2)
C
C  Calculate intensity at augmenter tube exit
      INTENS=WSURF/CROSSA
      PRINT*, " INTENSITY = ",INTENS,"WATTS/M^2"
      AUGSURF=10.0*LOG10(ABS(INTENS)/1.0E-12)
 360  FORMAT(2F10.1,F10.4,E13.3)
 365  FORMAT(5X,I3,5X,I3,5x,I3,8X,F8.3,3X,F8.3,3X,F8.3,3x,E14.3)
     END SUBROUTINE SURFNOISE
C
     SUBROUTINE REVERB(SUMJET,WSURF,DD,AugTubeL,AugShelD,AUGREVRB)
C  Calculate the reverberant field in and around the augmenter tube. The
C  jet noise and the surface noise are the noise sources.
     REAL DD,AugTubeL,AugShelD
     REAL WSURF,SUMJET
     CROSSA=0.785*DD**2
     PILLOA=3.1416*2.0*(DD+1.5)*(AugTubeL)
C  =2*PI*PILLOD*DUCTL=PILLOW AREA
      PILOALFA=0.9
      LINERA=3.1416*(AugShelD)*(AugTubeL)
C  =PI*LINERD*DUCTL =OUTER PIPE LINER
      LINRALFA=0.3
      AUGA=2.0*CROSSA
C  =2*(PI/4)*DUCTD^2= entrance and exit areas
      AUGALFA=1.0
C  Calculate absorptive power = sum of AREAi*ALFAi=WABS
```

```
      WABS=PILLOA*PILOALFA+LINERA*LINRALFA+AUGA*AUGALFA
      PRINT*, "WABS=",WABS," SUMJET=",SUMJET," WSURF=",WSURF
      PRINT*,"DD,AugTubeL,AugShelD,CROSSA=",DD,AugTubeL,AugShelD,CROSSA
C steady state acoustic intensity = power sources/absorptive power
      INTENS=(SUMJET+WSURF)/WABS
C The reverberant IL is reduced by the losses in the expansion
C chamber (test cell). deltaIL=10Log(1+(m-1/m)^2*sin^2(kC))
C where m=A2/A1=3.23,C=augtubeL=18.3m, and sin(kC) varies from
C 0<sin(kC)<1 across the spectrum, so use sin(kC)=0.707 (RMS).
C So deltaIL=10Log(1+1.06)=3.1 dB.
       A2=0.785*(AugShelD**2)
C Shell area=pi*(AugShellDia^2)/4
       A1=7.3
C Area of entrance to augmenter tube
        m=A2/A1
        ExpChmbr=0.5*(1.0+((m-1.0)/m))**2
        DeltaIL=10.0*LOG10(ExpChmbr)
      AUGREVRB=10.0*LOG10(INTENS/1.0E-12)-(DeltaIL)
C Intensity level
      PRINT*, "Reverberation field intensity level,IL=",augrevrb," dB"
      END SUBROUTINE REVERB
```